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A STUDY OF THE PULSE RATE IN MAN AS MODIFIED BY MUSCULAR WORK

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A STUDY OF THE PULSE RATE IN MAN, AS MODIFIED BY MUSCULAR WORK.

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The rapidly growing interest in gymnastic and athletic sports demands a more exact and comprehensive knowledge of the effects of muscular work upon the circulatory system. Without such knowledge, any rational supervision and guidance of such sports is an impossibility. While acting as director of a gymnasium the writer became impressed with the importance of securing further data on this question, and resolved to make, at the first opportunity, a study of the effects of muscular work on the heart. The present paper is to be looked upon as a preliminary report, dealing with but one phase of the question—the effect of work upon the rate of the heart.

Three methods have been employed in previous studies of the pulse rate in man: palpation of an artery, auscultation of the heart sounds, and graphic records of the pulse.

Palpation.—All studies of the pulse previous to 1850 were by palpation of some artery. The method was used from the earliest times, but the first recorded use of it to determine the effect of muscular work was in 1732, when Bryan Robinson counted a man's pulse in different bodily positions and after walking and running.[1] For more than a century after Robinson the only interest in the effect of work upon the heart seems to have been because of its being involved in the effect of position of the body, which was studied and discussed extensively.[2]

Within the last twenty-five years this method has been used to determine the rate of the heart after work of various kinds by Steiniger,[3] Lagrange,[4] Stekel,[5] Altschul,[6] Mendelsohn,[7] Athanasiu and Carvallo,[8] and a few others. The radial pulse has been counted during exercise by Salisbury,[9] who made

[1] Robinson: A Treatise on Animal Economy, London, 1734.
[2] Langovoy: Deutsches Arch. f. klin. Med., Vol. LXVIII, p. 294.
[3] Verhältniss des Pulses zum Schritt; Leipzig, 1870.
[4] Physiology of Bodily Exercise; New York, 1890, p. 97.
[5] See Schiffendecker, Schmidt's Jahrbuch, Bd. CCLXX, p. 123.
[6] Münch. Med. Wochenschr., 1898, p. 1559.
[7] Prophylaxe der Herzkrankheiten, Munich, 1901.
[8] Arch. de Physiol. Norm. et Path., 1898, p. 360.
[9] Am. Journ. Med. Sc., 1866, Vol. 52, p. 92.

a brief study of the effect of talking and of mild arm movements; by Dehio,[1] whose subjects lifted a weight with the foot while lying upon the back; and by Grünbaum and Amson,[2] who have studied the effect of work done upon several gymnastic machines. In the latter research, which is without doubt the most extensive and accurate study of the effects of work made by this method, the traditional practice was modified by counting a definite number of beats and recording the corresponding time with a stop watch.

Auscultation.—Two interesting studies of the time relations of the cardiac cycle have been made by auscultation of the heart sounds. Donders[3] investigated the relative duration of systole and diastole with various pulse rates, using the stethoscope in the usual way upon the human subject, recording the time of the sounds by tapping a key connected with an electric signal which, along with a chronograph, marked on a moving surface. He used muscular work as a means of increasing the pulse rate, but all his records were taken after the work ceased.

Hering,[4] working upon dogs, studied the functions of the cardiac nerves. He recorded the respiratory movements by a modification of Marey's method of air transmission, and connected his stethoscope with the rubber bulbs which served as receiving instruments. He was able to count the pulse in this way during both rest and work.

Graphic records of the pulse date from the invention of the sphygmograph by Vierordt in the early fifties.[5] His instrument was soon improved upon, and the principle was extended by Marey and others to the taking of records from other arteries than the radial, thus multiplying the possibilities of the method; but it was many years before the effects of muscular work received more than occasional and incidental attention. In 1863 Marey[6] published records of the pulse taken during inspiratory and expiratory efforts, incidental to an investigation of the effect of respiratory movements on the circulation. Thurston,[7] Edgren,[8] and Chapman,[9] using the graphic method, made extensive studies of the changes in systole and diastole accompanying changes in pulse rate. Here muscular work was used as a convenient means of quickening the pulse, but apparently was not of itself of any interest to the investigators.

Within the last decade the sphygmograph has been used in at least six

[1] St. Petersb. Med. Wochenschr., 1901, p. 79.
[2] Deutsches Arch. f. Klin. Med., Bd. LXXI, p. 539.
[3] Dublin Journ. Med. Sc., Vol. XLV, p. 225.
[4] Arch. f. d. ges. Physiol., Bd. LX, p. 429.
[5] See Landois: Arterienpuls; Berlin, 1872.
[6] Physiologie Medicale der Dang., Paris, 1863, p. 296.
[7] Journ. Anat. and Physiol., Vol. X, p. 494.
[8] Skandin. Arch. f. Physiol., Bd. I, p. 67.
[9] Brit. Med. Journ., 1894, I, p. 511.

different studies of the effects of muscular work. The work of Kolb,[1] extending over several years and including many kinds of athletic and gymnastic exercises, was published in England in 1892. Two years later Herman Christ[2] published a study of the pulse before and after work done upon Dr. Jacquet's stair apparatus, using normal individuals and convalescents as subjects. The work by Christ was continued by Staehelin.[3] Egger[4] studied the effect of pain, using the effect of light work as a control. Babbitt[5] made studies similar to those of Kolb. Zuntz and Schumburg[6] made an exhaustive study of the physiology of marching, including pulse records. In all these investigations the ordinary clinical instruments were employed and applied as usual to the radial artery. The studies were limited to the periods before and after the work.

The plethysmograph has been used in studying the pulse by Athanasiu and Carvallo[7] and by Binet and Courtier.[8]

In addition to the work done upon man, much valuable information has been secured upon this subject through work done upon animals by Marey,[9] Kaufmann,[10] Johansson,[11] Jacob,[12] MacWilliam,[13] Hunt,[14] and others. These investigators made use of a mercury manometer connected with a cannula inserted in an artery.

The superiority of the graphic method in a study of this kind over any method involving the observation of a series of phenomena by a single observer is obvious. A graphic record includes more than can be grasped by any observer, no matter how well trained. The records being preserved and read repeatedly, the chance of error is greatly reduced. Time relations can be worked out on a graphic record with a precision which cannot be approached by direct observation. But the sphygmograph and the plethysmograph, the two instruments hitherto used in studies of the pulse, are so sensitive to any movement or jar that the most essential part of the problem—the period during the work—must be given up if the work is at all vigorous. Not wishing to

[1] Physiology of Sport, London, 1892.
[2] Deutsches Arch. f. Klin., Bd. LIII, p. 102.
[3] Deutsches Arch. f. klin. Med., Bd., LIX, p. 79; LXVIII, p. 147.
[4] Arch. f. Psychiat., Bd. XXXI, p. 274.
[5] Am. Physical Education Review, 1901, p. 240.
[6] Physiologie des Marsches; Berlin, 1901.
[7] Loc. cit., p. 351.
[8] L'année Psychologique, 1896, p. 30.
[9] Loc. cit.
[10] Arch. de Physiol., 1892, pp. 279 and 495.
[11] Skandin. Arch. de Physiol., Bd. V, p. 20.
[12] Arch. f. Anat. and Physiol., 1893, p. 305.
[13] Proc. Roy. Soc., London, 1893, p. 464.
[14] Am. Journ. Physiol., 1899, II, p. 395.

be subject to such limitations, the writer made a series of trials of different forms of appliances, and finally decided upon the apparatus described in the next section.

Methods Employed in this Research.

A graphic record of the pulse is taken from the carotid artery by means of two tambours connected by a tube. The receiving tambour, made from a tin box-cover, is 5 cm. in diameter and 1.5 cm. deep. This tambour is without the usual membrane, the open side being pressed against the skin of the neck over the artery by a U-shaped spring, one end of which is connected with the tambour by a ball and socket joint, while the other end terminates in a rounded block which bears against the opposite side of the neck. To prevent the edge of the tambour from cutting the skin, a wire rim was put on so as to give a bearing surface 2 mm. wide. The connecting tube, which leaves the tambour from the side, is of light rubber near the neck, where lightness and flexibility are required; but as much of it as possible is of thick-walled rubber or glass. A tube of between 3 and 5 mm. bore gives best results. At some point in the tube a glass T-tube is inserted, and the side tube is fitted with a short piece of rubber tubing. The side branch is left open while the apparatus is put in place and adjusted, and is closed with a spring clip when a record is desired.

One point in favor of this apparatus is its convenience of application; it requires but an instant to put the receiving tambour in place or to remove it. The essential point in which it differs from the similar instruments used by Marey and Edgren is the application of the tambour directly to the skin, without any intervening button or membrane. This greatly reduces the disturbing influence of movements of the body, but it does not entirely prevent them. It is therefore necessary to choose kinds of work in which the neck can be held comparatively still.

The recording tambour is 1.5 cm. in diameter and is covered with a thin rubber membrane, which transmits its movements to the recording surface by a light celluloid lever.

Three electro-magnetic signals are used. One, connected with a pendulum or fork, records the time; another, connected with the apparatus upon which work is done, records each movement or revolution; the third is used to indicate the time relations of two records taken at once, as described on page 489.

The recording tambour and signals are mounted on a steel rod one foot in length, whose ends turn freely in sockets. The two sockets are clamped to two other rods, which in turn are clamped to a rigid support in such positions that the first rod turns in a vertical plane. The support is fastened to the table at a proper distance from the kymograph, and a horizontal rod is clamped to the pivoted rod so that it will strike the support just as the writing points reach the paper. A light rubber band holds the apparatus in this position

while a record is being taken, and a weight suspended by a cord passing over a pulley turns the writing points away when desired.

The tambour recording the pulse is so placed that the axis of its writing lever is on a level with the writing point of the signal which records time, and the lever of the tambour is adjusted to write slightly above the time record. With this arrangement the correct time relations of the pulse curve can be found by simply describing arcs cutting the two records, the radius being the length of the writing lever, and the center on the base line of the time record. This plan avoids the construction of a perpendicular for each interval measured, and thus saves a vast amount of time and lessens the chance of errors.

The records are taken on papers 13 cm. wide and from three to five meters in length, which pass around two drums; one of these is the drum of a heavy kymograph, and the other a smaller one made of a section of brass tubing 5 cm. in diameter. The smaller drum is mounted on a rod whose beveled ends turn in sockets, and these are clamped to two horizontal rods, which are fastened to a rigid iron supporting standard. One leg of the latter is pivoted, allowing sufficient adjustment for tightening the paper. When the time is recorded in seconds, a continuous record can be taken by the use of one meter of paper for each four or five minutes; when a fork curve showing fiftieths of a second is recorded, a meter of paper is required for each thirty seconds.

The table supporting the recording apparatus is fastened to the wall of the building, to avoid vibrations of the floor. The apparatus upon which work is done is placed on the floor and brought as near this table as possible, to avoid long connecting tubes.

In the experiments made thus far, heavy and moderate work has been done upon a lathe and a bicycle, while a telegraphic key has been used in studying the effects of the lightest work.

The lathe is worked by a treadle moving through an arc of 15 cm. and carries a 55 pound fly-wheel 23 inches in diameter. A wooden lever rests in a polished groove in the rim of the fly-wheel, and a weight which can be moved along the lever provides a resistance which can be varied from 5 to 25 kg. The record is taken while the subject stands beside the lathe and rests more or less of his weight upon it by his arms, to prevent oscillations of his body, while he works the treadle with one foot. The movements are such that oscillations of the body are troublesome; and although several successful experiments have been made upon it, the lathe has been replaced in later work by the bicycle.

The frame of a bicycle is fastened rigidly upright, the wheels removed, and the chain carried beyond the rear of the frame to a sprocket mounted on a shaft which carries a heavy fly-wheel and a broad band-wheel with a polished surface. While searching for such material in the scrap-room of a

machine shop an old grindstone was found which answered the requirements without other labor or expense than the addition of the sprocket. The stone weighs about 125 pounds, is well centered on a shaft which also carries a suitable band-wheel and is mounted on a heavy iron frame. A piece of leather belting is fastened at one end, passed half way round the band-wheel, and attached to a weight-holder at the other end, making it possible to vary the resistance at the pedals from 4.5 kg. up to any desired amount by the addition of weights. The handle bars are set firmly in one position, and an adjustable wooden support helps to hold the rider's shoulders steady. The momentum of the fly-wheel carries the pedals past the "dead point," so that the sensation produced while running the machine is quite like that experienced in riding a bicycle on a smooth road. By using toe-clips and taking care to pedal evenly, one can work upon this machine almost to the limit of his strength and record a pulse curve in which the pulse beats can be counted readily and a large per cent of them analyzed. (See Figs. 1 and 7.)

The telegraph key is operated with the forefinger, and has a range of movement of 1 mm. and a resistance which varies between 40 and 4,000 grams. The subject is seated before the table upon which the key is fastened, his arm resting on the table, to avoid the necessity of any movement or effort other than that required to move the key.

All the experiments were made first with the writer as the subject; then they were repeated upon others as many times as circumstances permitted. The writer's age is thirty-eight, height and weight medium, health good; accustomed to a large amount of exercise from 1890–1900, but having much less of it at present. The other subjects have been men in good health, but not in athletic training, mostly medical students between the ages of twenty and twenty-five.

The Change in Pulse Rate when Muscular Work Begins.

1. *The Latent Period.*—With the beginning of muscular work the pulse quickens with surprising promptness and rapidity. To find how soon the acceleration begins, a series of experiments were made in which the work consisted in tapping the key as rapidly as possible, the records being taken with rapid drums and timed with a fork. The general character of the records is shown by Fig. 2; the results are given in Table I.

As may be seen by a glance at the table, the four heart cycles immediately preceding the beginning of the work show changes in duration such as are usually seen in the pulse of a resting subject; changes that in the main are small, the length of the cycle alternately increasing and decreasing with a rhythm which differs in the different cases, and which therefore cannot be due to the work nor to any constant condition of the experiments.

TABLE I.

DURATION OF CONSECUTIVE HEART CYCLES IN HUNDREDTHS OF A SECOND.

Subject.	Before Work.	Work b'gins	During Work.	Work ends.	After Work.
W. P. B	76, 76, 78, 78	74	70, 66, 64, 62, 64.. 60, 62, 62, 62, 64	64	64, 66, 68, 74
"	78, 80, 77, 80	82	73, 69, 70, 70, 67.. 67, 66, 66, 65, 63	66	67, 74, 72, 73
"	76, 74, 75, 78	77	72, 68, 66, 70 .. 68, 70, 69	66	70, 72, 74
O. M. C.	88, 90, 96, 100	98	90, 82, 74, 74, 74.. 74, 74, 72, 70, 76	74	80, 86, 86, 84
E. A. B.	76, 78, 78, 80	80	76, 64, 60, 60, 64.. 60, 66, 64, 66, 64	64	68, 74, 76
G. R.	84, 84, 88, 88,	90	80, 78, 76, 74, 68.. 70, 76, 76, 74, 74	74	72, 78, 86, 84
H. H. P ...	92, 94, 88, 90	90	84, 82, 76, 74, 70.. 70, 64, 62, 60, 58	58	62, 74, 72, 76
R. C. R.	94, 88, 90, 90	92	86, 82, 74, 72, 72.. 70, 76, 78, 74, 74	74	88, 90, 96, 90
C. J. L.	90, 94, 96, 98	90	86, 84, 70, 70, 70.. 70, 80, 84, 76, 82	76	76, 82, 88, 84
W. P. B. ...	76, 72, 72, 76	78	74, 70, 66, 64, 62.. 64, 60, 62, 62, 64	64	66, 68, 74, 76
" ...	74, 76, 74, 72	74	70, 66, 62, 62, 64.. 62, 64, 62, 62, 64	64	68, 66, 70, 72
" ...	77, 81	83	80, 77, 74, 70, 71.. 70, 71, 69, 69, 67	70	79, 85, 89, 92
" ...	77, 82, 85, 83	80	79, 70, 65, 64 .. 65, 65	73	81
" ...	89, 92, 93, 89	83	77, 74, 75, 73, 76.. 73, 76	78	81, 93, 89
" ...	85, 89	92	83, 74, 74, 72 ..76, 78, 77, 79, 82, 83	85	86, 84
" ...	72, 72, 72, 72	71	66, 66, 66, 64, 64..		
" ...	68, 70, 72, 66	66	64, 62, 64, 64, 62..		
" ...	93, 89	92	88, 77, 76		
B. D. N. ...	92, 96	88	86, 84		
" ...	84, 82, 84	80	78, 76		
" ...	84, 90	90	78, 80, 80		
" ...	80, 78, 80	80	78, 70		
" ...	80, 84	80	76, 74, 75		

The causes of this variation in the length of the heart cycle in the resting subject have been investigated at great length, Traube,[1] Hering,[2] Sommerbrodt,[3] Fredericq,[4] and Gley[5] being prominent among earlier investigators, while Binet and Courtier[6] and Lombard and Pillsbury[7] have studied the subject more recently. As the result of all this work the minor changes in the duration of the cycle during rest are believed to be due to respiratory, vasomotor, and psychic changes.

These changes appear to continue without interruption into the cycle in which the work begins, for this cycle has the same average length as the preceding one, while as to the phase of the change there are eight cases with an increased length, ten cases with a decrease, and five cases with no change. Some of these cases of decrease in the length of the cycle may be due to the work, or partly so; but in view of the fact that on the whole the changes are substantially the same as in the cycles preceding, it is not safe to assume that the work has had any effect at all up to this time.

With the next cycle after the work begins there is a marked change. The cycle is shorter than the one before in every case; the amount of the change is in general much greater than the preceding changes; and the decrease con-

[1] Centralbl., f. d. Med. Wissensch., 1865, p. 881.

[2] Sitzungsb. d. k. Akad. d. Wissensch., Wien, 1869, XL.

[3] Deutsches Arch. f. klin. Med., Bd. XXIII, p. 542.

[4] Arch. de Biol., 1882, III, p. 55.

[5] Arch. de physiol. norm. et pathol., 1881, p. 742.

[6] L'année psychologique, 1896, p. 42.

[7] Amer. Journ. Physiol., Vol. III, p. 201.

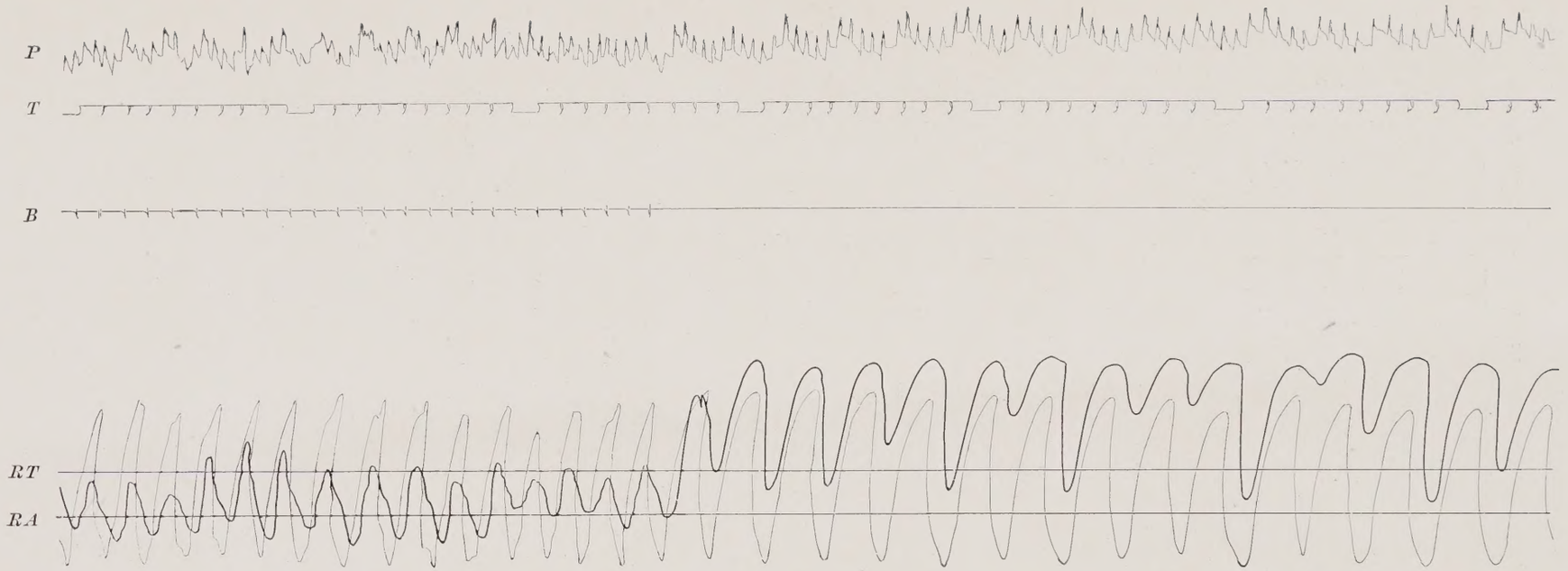

FIG. 1. Example of record taken on slow drum. *P*, pulse curve; *T*, time in seconds; *B*, signal marking each revolution of bicycle crank; *R*, thoracic and abdominal respiratory movements. This record shows the changes at the end of the work in Experiment 11 of Table IV.

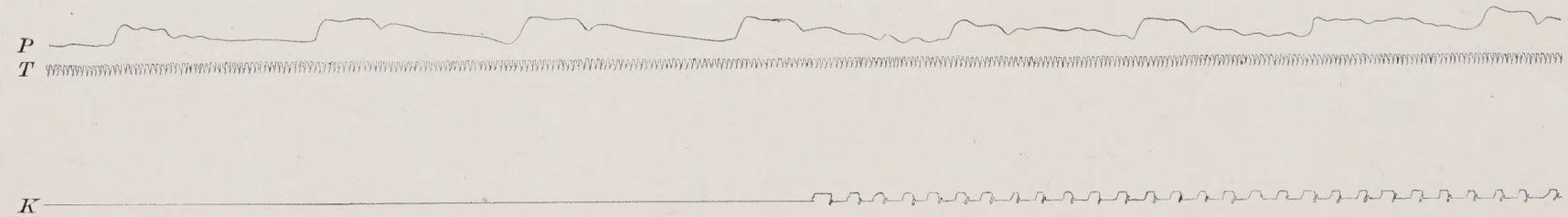

FIG. 2. Example of record taken on fast drum, showing change at the beginning of light and rapid work. *P*, pulse curve; *T*, time in fiftieths of a second; *K*, movements of telegraph key.

tinues without interruption for several cycles following. Such changes must without question be attributed to the work.

The number of these experiments is too small to serve as the basis of an exact determination of the latent period, but the change is so prompt and so constant in response to the work that it may be used in arriving at a rough approximation. It must be observed first of all that it is not possible to begin the work in each case at a chosen point in a cycle; the beats follow each other too quickly. In this series the records show that the work began in the first quarter of the cycle in five cases, in the second quarter in five cases, in the third in seven cases, and in the last quarter in six cases. It will be shown in a later section of this paper that the acceleration of the pulse at the beginning of muscular work is wholly due to a shortening of the diastole; in other words, we have no evidence from the pulse curve of any response on the part of the heart until *the end* of the next cycle after the work begins. The *delay,* therefore, which occurs between the beginning of the work and the first evidence of quickened heart action shown by the pulse curve varied in the twenty-three cases between one and two heart cycles as its extreme limits.

The variation in the length of the delay is evidently due to variation in the time of beginning the work. For example, the two cases in which the work began earliest in the cycle show a delay of 1.49 seconds, while the six cases in which it began in the last quarter of the cycle show delays varying between 0.85 and 1.11 seconds; the delay being longer in the first instance simply because the work began farther away from the first point on the pulse curve at which a change in pulse rate can be observed. It follows that the latent period of the heart when influenced by muscular work cannot be far from the shortest delays observed, or about the length of one cardiac cycle, which varied in the present cases from 0.64 to 0.90 seconds.

It is interesting to notice in this connection that Donders[1] found a latent period of the dog's heart, when influenced through the vagus nerve, varying from .6 to .8 of a cardiac cycle. By cutting the vagus in the dog Hunt[2] obtained a shortening of the cycle in which the cutting occurred; he also obtained by stimulation of a sensory nerve a shortening of the next cycle after the work began, and by stimulation of the accelerator nerves a shortening which took place after a delay of several seconds.

2. *The Manner in which the Pulse Rate Changes.*—Another important point brought out by the results in Table I is the rapidity with which the pulse rate changes at the very start. A glance at the table is sufficient to observe this in a general way, but since the minor changes in rate that have been mentioned continue into the period of work and cause small irregularities, we get a more definite picture of the change from averages. The last

[1] See Tigerstedt's Physiologie des Kreislaufes, p. 239.

[2] Loc. cit., pp. 436, 441, 438.

eight cases in the table were taken to study latent period only, and do not include enough cycles for the present purpose; excluding these and taking the average duration of consecutive cycles from the remaining fifteen cases we have: before the work begins, 82.3, 83.0, 83.4, 84.8; at the time of beginning, 84.2; and during work, 78.6, 73.7, 69.4, etc. The average duration of the cycles preceding the work and including the one in which it began show only minute variations, but with the commencement of the work we have a shortening amounting to 17.5 per cent within the time of three cycles; and of the three the change is greatest in case of the first one.

In order to study the manner of this change through the entire period of acceleration, records were taken during work lasting from one to six minutes. In these experiments the records were taken on slowly moving drums and timed in seconds. The results are given in Tables II, III, and IV with sufficient fulness for present purposes. In compiling the tables the number of pulse beats for each period of ten seconds was first determined from the records; each of these numbers was then multiplied by six, giving the pulse rate per minute for the consecutive periods, as shown in the tables.

In each experiment we find immediately after the beginning of the work a rapid rise in pulse rate, which will be called the *primary rise.* This rise, after continuing for a period varying from ten seconds to two minutes, gives place to an approximately uniform portion, which will be spoken of as a *plateau.* For the sake of clearness it is assumed that the primary rise continues until it merges into a plateau lasting at least thirty seconds. Any further prolonged rise will be called a *secondary rise;* any brief rising and falling of the rate will be called *minor changes.*

Table II.

Pulse Rates per Minute for Consecutive Periods of Ten Seconds, Showing the Effect of Tapping a Key Rapidly for Periods Varying from One to Six Minutes. (Seven Subjects.)

Number of Experiment	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Before Work	66.0	75.0	69.0	75.6	64.8	79.2	60.0	58.8	53.4	66.0	65.4	67.8	72.0	72.6
	68.4	75.0	63.0	78.0	64.8	78.0	66.6	60.0	52.2	69.0	70.2	66.6	72.0	75.0
	66.0	78.0	67.2	75.0	66.0	76.2	67.0	63.0	54.0	67.2	72.0	65.4	72.0	72.0
During Work	76.8	96.0	85.8	86.4	78.0	87.6	84.0	69.0	66.0	78.0	81.0	72.0	78.6	87.6
	84.0	102	94.8	87.0	84.0	92.4	97.2	80.4	72.0	78.6	81.0	81.0	85.8	91.2
	88.8	105	99.0	90.0	86.4	102	102	83.4	81.0	82.8	81.0	82.2	88.2	90.0
	89.4	102	96.0	90.0	90.0	100	102	81.6	84.0	84.0	80.4	84.0	94.2	92.4
	90.0	99.0	97.8	90.0	90.0	102	102	88.2	84.0	84.0	83.4	83.4	94.2	90.0
	92.1	103	87.0	93.6	85.2	90.0	97.2	96.0	84.0	...	80.4	...	88.6	90.0
	91.2	102	92.4	92.4	86.0	90.0	94.8	96.0	84.0	84.0	78.6	83.4	90.0	90.0
After Work	67.8	68.0	82.8	81.0	86.0	81.6	81.0	73.2	66.0	76.8	72.0	78.0	84.0	75.0
	66.0	66.0	76.2	78.0	60.0	78.0	73.2	66.0	64.2	72.0	67.2	72.0	80.4	77.4
	67.8	67.8	72.0	78.0	60.0	78.0	73.0	60.0	64.2	70.8	67.2	69.6	81.0	72.0
	66.6	66.6	73.2	73.2	60.0	79.2	69.0	61.2	58.8	67.8	66.6	66.0	80.0	...

TABLE III.

PULSE RATES PER MINUTE FOR CONSECUTIVE PERIODS OF TEN SECONDS, SHOWING THE EFFECT OF FIVE MINUTES OF LATHE WORK. WORK DONE BY ONE SUBJECT.

Experiment Number.	1	2	3	4	5	6	7	8	9	10
Before Work	69.0	66.0	60.0	64.0	69.0	70.8	72.0	73.2	75.0	78.0
	69.0	66.0	58.8	67.8	66.0	60.0	72.0	72.6	75.0	71.4
	72.0	67.2	58.8	69.0	64.8	60.0	72.0	73.8	76.2	68.4
During Work	81.6	84.0	78.0	*	87.0	*	90.0	*	*	*
	90.0	87.0	82.8	82.2	96.0	93.0	102	100	104	108
	90.0	84.0	86.4	88.8	98.4	99.0	111	112.2	109.8	124.2
	90.0	87.0	87.0	90.0	96.0	100.8	114	126	120	134.4
	90.0	84.0	84.0	91.8	99.0	106.8	120	132	132	144
	90.0	84.0	84.0	93.0	99.0	114	126	138	138	150
	90.0	87.0	86.4	93.0	99.0	117	135	144	141	156
	90.0	82.8	87.0	93.0	100	126	141	144	142.2	156
	90.0	88.2	84.0	90.0	100	126	144	156	144	156
	88.8	91.2	90.0	94.2	105	129	144	150	150	163.8
	88.8	94.8	90.0	94.8	102	132	144	156	150	163.8
	88.8	90.0	90.0	90.0	105	132	144	150	153	156
After Work	84.0	75.0	75.0	81.6	84.0	105	126	144	121.8	138
	75.0	72.0	67.8	78.0	78.0	96.0	120	126	111.6	121.8
	72.0	71.2	64.8	72.0	72.0	93.0	114	123	106.8	115.2
	72.0	67.8	62.4	72.0	69.0	90.0	114	111	102	112.8
	72.0	69.0	62.4	66.0	69.0	87.0	112.4	109.2	96.0	111
	72.0	66.0	60.0	64.8	66.0	84.0	105	108	96.0	112.2

* Pulse curve not legible.

TABLE IV.

PULSE RATES PER MINUTE FOR CONSECUTIVE PERIODS OF TEN SECONDS, SHOWING THE EFFECT OF FIVE MINUTES OF BICYCLE WORK. WORK BY ONE SUBJECT, EXCEPT IN 10.

Experiment Number.	1	2	3	4	5	6	7	8	9	10	11
Sitting in Chair	61.2	56.4	56.4	76.2	70.8	71.4	79.8	76.2	79.2	72.0	66.0
	61.2	56.4	56.4	69.6	68.4	71.4	77.4	76.8	78.0	75.0	68.0
	64.8	58.8	56.4	70.8	70.8	73.2	79.8	73.2	77.4	74.2	67.2
Upon Bicycle	70.8	61.2	61.6	73.2	70.2	78.6	82.2	79.2	81.0	80.4	78.0
	66.0	60.6	61.2	72.0	70.8	76.8	82.2	79.2	82.2	80.4	78.6
	72.0	66.0	64.2	74.4	73.2	75.6	83.4	83.4	82.8	76.8	80.4
During Work	78.0	80.4	78.0	84.0	96.0	99.0	102	97.8	102	93.0	100.2
	80.4	79.8	87.0	96.0	100.8	108	106.2	108	120	100.8	112.4
	79.2	82.8	90.0	96.6	103.2	115.8	109.8	117.6	132	105	116.4
	73.2	82.2	93.0	99.6	107.4	123	112.8	124.8	142.2	108.0	118.8
	76.8	76.2	90.0	102	109.8	128.4	114	130.8	150	112.2	121.8
	76.0	78.0	89.4	100.8	111.6	129	114	136.8	144	116.4	126
	76.2	80.4	96.0	97.8	114	130.8	120	139.2	144	123.6	132
	75.0	82.8	96.0	97.2	115.2	132	117	142.8	156	126	132
	80.4	82.2	95.4	96.0	115.2	132.4	117	144.6	162	126	132
	82.2	84.0	93.0	102	115.2	136.8	120	147	168	126	132
	77.4	84.0	97.2	98.4	114	136.8	118.2	148.2	168	126	132
	78.0	78.0	93.6	97.2	111	132	121.2	150	180	126	138
	73.8	80.4	94.8	91.2	113.4	147	123	156	180	142.4	144
	73.2	80.4	96.0	94.2	110.2	144	120	156	180	144	144
	78.0	80.4	96.0	94.8	109.8	144	122.4	159	180	141	144
After Work	73.2	73.2	86.4	90.0	102	135	111	150	174	132	138
	67.8	72.0	79.2	81.0	94.8	129.6	105	138	162	132	126
	64.8	67.2	75.6	79.2	90.0	120	98.4	126	156	126	117
	65.4	64.8	72.0	73.2	87.6	110.4	102	120	151.6	114	114
	66.0	63.6	68.4	72.0	82.8	108.2	102	117	147.6	104.4	108
	70.8	64.8	67.8	72.0	78.0	102	97.2	120	142.2	99.0	110

It is desirable to study the average of the pulse rates given in a series of cases when permissible, to throw out the disturbing minor changes. Taking an average of the fourteen cases of Table II during the primary rise we have as follows:

	Before work.	During Work.				
	Last 10 sec.	1st. 10 sec.	2d. 10 sec.	3d. 10 sec.	4th. 10 sec.	5th. 10 sec.
Average rate per minute	68.6	80.5	86.5	89.4	90.7	91.3
Increase over preceding period		11.9	6.0	2.9	1.3	0.6

It is plainly the rule here for the acceleration to be most rapid at the start and for the amount of change in each successive period to become less and less until the primary rise is finished. Plotting a curve to represent the average

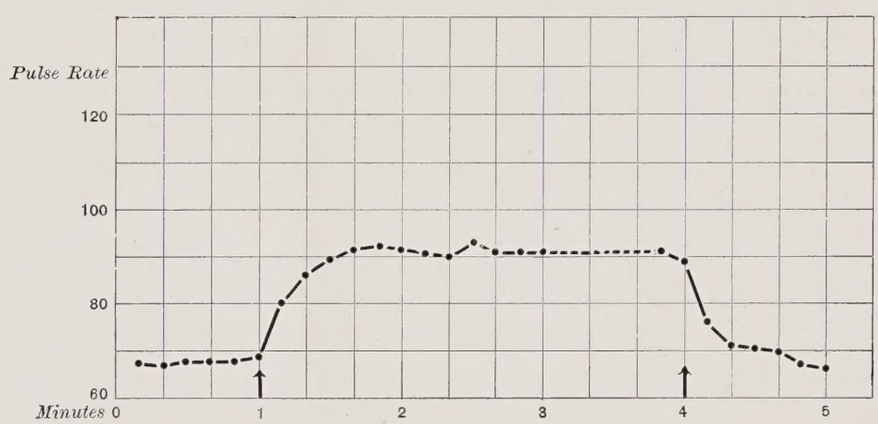

FIG. 3. Curve of pulse rate, showing the effect of tapping a key rapidly. Plotted from the average of the fourteen cases of Table II. Arrows indicate the time of beginning and stopping work.

pulse rate of the fourteen cases, laying off units of time as abscissæ, and pulse rates per minute as ordinates, we obtain the curve shown in Fig. 3.

In the experiments of Tables III and IV there was such wide variation in the speed and intensity of work that an average is hardly practicable; but the results given in these tables agree with the above rule in every case, except as minor changes cause apparent exceptions in some instances in the later stages of the acceleration, when the changes due to the work have become small. Choosing Experiment 8 of Table IV as a typical example and plotting its curve we obtain Fig. 4. Figs. 3 and 4 picture clearly the character of the primary rise: very rapid at first, then gradually subsiding, and finally merging into a plateau.

There are some small irregularities in these tables which result from the manner of reading the curves. It rarely happens that the line separating the

periods of ten seconds coincides exactly with the beginning of a primary pulse wave, and consequently fractions of cycles are of common occurrence in the results. It was not considered necessary, in view of present purposes, to measure the fractions of cycles accurately, but instead they have been estimated carefully by the eye with the aid of a hand lens. It may be observed that in Table III the fractions are not estimated so closely as in II and IV. This is because in the lathe work oscillations of the body caused slight defects in portions of the record, making it impossible to determine the fractions as accurately as

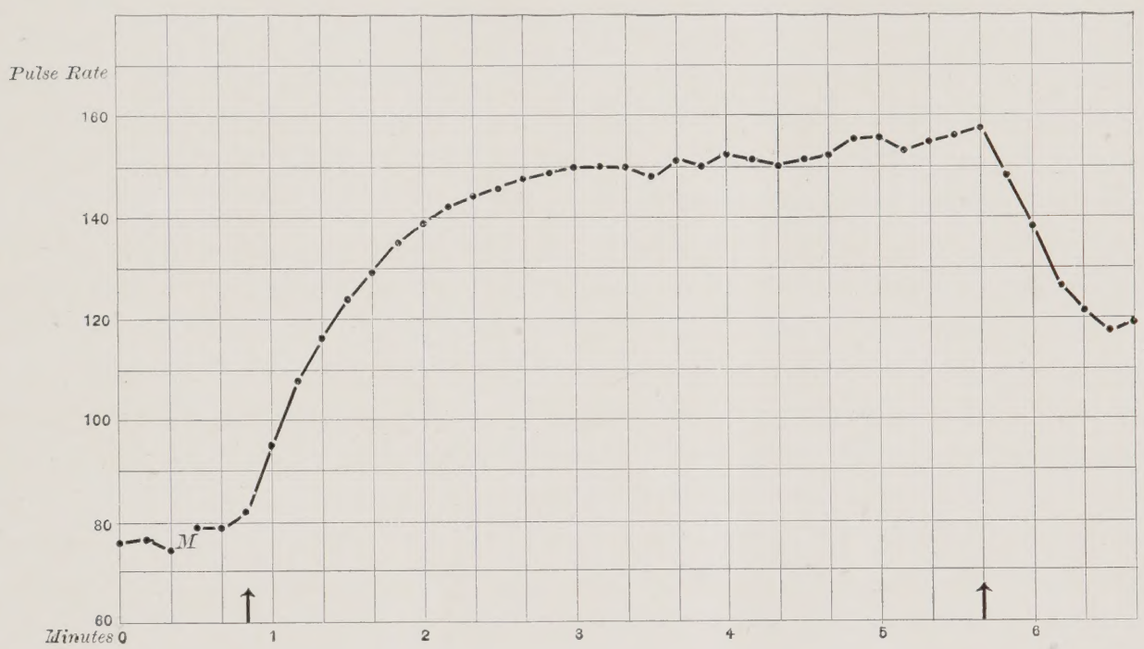

FIG. 4. Curve of pulse rate, showing the effect of five minutes of vigorous work on a bicycle. Plotted from results of Experiment 8 of Table IV. *M*, mount; arrows indicate time of beginning and stopping work.

in other work. The irregularities in Table II during the period of the plateau are no doubt due, in part, to changes in the speed and force of the work. All of these changes, however, are so small in comparison with those resulting from the work that they can have practically no effect on the general form of the primary rise, as illustrated by Figs. 3 and 4.

The superiority of the graphic method for studies of this kind is well illustrated by the completeness and accuracy with which these results show the sudden and rapid primary acceleration of the pulse under the influence of work. Grünbaum and Amson[1] have been over this ground with great care, using the most perfect method of direct observation of the pulse ever employed; yet, since they could not determine the duration of individual beats, they could not find the exact manner of the change nor the latent period; and since they could not count uninterruptedly, they missed critical periods. In fact, their

[1] Loc. cit., pp. 557–586.

protocols show that they missed in every case the few seconds during which the change is most rapid. This will account for some minor differences between their curves and mine.

3. *The Causes of the Primary Rise.*—The rate of the heart can be influenced by two groups of causes; those acting directly upon the heart, and those acting indirectly through the nervous mechanism which controls it. Among influences acting directly upon the heart may be mentioned heat and waste products carried from the working muscles in the blood stream; probably heat and waste products formed in the heart as the result of its own increased activity; and circulatory conditions determining the supply of blood to the heart and resistance to the discharge of blood by it. The nervous mechanism which controls the heart is influenced by a similar set of conditions: heat and waste products brought by the blood, changes in blood pressure, and above all by nervous impulses coming from all parts of the body.

When we compare the latent period of the heart and the rapidity of the primary acceleration of the pulse with the time required for these various causes to become effective, we are compelled to conclude that the only influence acting quickly enough to account for the first change in pulse rate when muscular work begins is that of nervous impulses arising in the motor centers of the cerebral cortex and in the muscles, and acting upon the inhibitory center. In some cases of heavy work what we have called the primary rise lasts long enough for all of these causes to become effective; in some cases of light work, the plateau is reached so soon as to exclude all of them except the effect of nervous impulses acting on the heart centers.

Consider first the causes acting directly upon the heart. The effect of waste products in the blood has been studied by Johansson[1] and by Athanasiu and Carvallo,[2] who found that these were capable of quickening the heart beat. Neither of these authors gives the length of the latent period of this effect, but both say that it is long. The products of metabolism, before they can act upon the heart, must traverse half of the systemic circulation, the whole extent of the pulmonary circulation, and enter the coronary arteries from the aorta. According to the more recent estimates of the circulation time in man this must require from thirty-six to forty-five seconds,[3] if we make no allowance for the diffusion of the waste products from the tissues into the blood. All investigators agree that the acceleration of the heart caused by waste products comes on slowly and increases gradually as work continues. It is certain, therefore, that this cause cannot account for the first change in pulse rate.

[1] Loc. cit., pp. 60–62.

[2] Loc. cit., p. 561.

[3] Stewart: Manual of Physiology, Phila., 1900, p. 124; Richet: Dictionaire de Physiologie, see *Circulation.*

The heat developed in the working muscles, like the waste products, must travel in the heart in the blood stream before it can influence the rate of the beat; it cannot, therefore, become effective in causing acceleration much sooner than the waste products.

Anything which causes more rapid filling of the heart thereby tends to quicken the beat, but there is no conceivable way in which light work can bring this about the instant the work begins, unless it should be through a compression of the abdomen causing an emptying of the abdominal veins. An act involving violent effort often causes strong contraction of the abdominal muscles and consequent compression of the abdominal viscera; but this phenomena is not marked in light work, and cannot account for the first acceleration, which comes so promptly, even in the lightest work. Several tests were made of the effect of compressing the abdomen strongly by means of a strap, but the acceleration of the pulse produced was very slight and lasted only a few seconds.

Marey[1] and Kaufmann,[2] who worked upon the horse, lay great stress upon the dilation of peripheral vessels and the resulting fall of blood pressure as the cause of the increase in heart rate during work. Work cannot bring about the first beginning of dilation of vessels in less than three seconds,[3] and according to MacWilliam[4] it requires about thirty seconds to cause any increase in the heart rate after a considerable fall of blood pressure has taken place. Even if we assume that the results obtained by Marey and Kaufmann hold good in case of man, we must still look elsewhere for the cause of the first acceleration at the beginning of the muscular work.

Contrary to the theory of Marey and Kaufmann, most recent observers[5] agree that muscular work causes a rise of blood pressure in man. It is not at all probable that a rise of blood pressure would cause an increased pulse rate; but in the absence of positive proof it may be well to consider the time involved. As stated by Tigerstedt,[6] the height of the blood pressure at any time depends upon: (1) the resistance of the peripheral vessels; (2) the mass of blood in circulation; and (3) the energy of the heart's action. A constriction of peripheral vessels by action of the vasomotor center requires at least 1.5

[1] Loc. cit.

[2] Loc. cit., pp. 279, 497.

[3] Francois-Franck: Travaux du Laboratoire de Marey, 1876, p. 39; and Bowditch and Warren: Journ. Physiol., 1886, VII, p. 440.

[4] Loc. cit., p. 470.

[5] Edgecumbe and Bain: Journ. Physiol., Vol. XXIV, p. 48; Maximowitsch and Rieder: Deutsches Arch. f. klin. Med., Bd. XLVI, p. 329; McCurdy: Am. Journ. Physiol., Vol. V, p. 95; Kornfeld: Wiener Medicinische Blätter, 1899, p. 631; Masing: Deutsches Arch. f. klin. Med., 1902, Bd. LXXIV, p. 253.

[6] Loc. cit., p. 332.

seconds.[1] The work cannot instantly increase the mass of blood in circulation except through effort great enough to compress the abdominal viscera and drive blood from there into the general circulation; a result not produced in light work, as previously stated. It is very improbable that increased pressure can have anything to do with the first increase in pulse rate accompanying light work. Most observers report that changes in arterial pressure have little or no immediate effect on the rate of the pulse.[2]

A cause of increased heart rate which I have never seen mentioned as such is the formation of heat and waste products in the heart itself, as the result of its own increased activity. This cannot of course take place at the beginning of the acceleration, but in consideration of the very rapid rate that we find accompanying work, it may well be considered as an influence of considerable importance later.

Causes influencing the heart through its nervous mechanism show a marked difference in effect depending upon which of the cardiac nerves is involved. Withdrawal of the inhibitory influence of the vagi increases the pulse rate rapidly after a short latent period; increase of accelerator influence increases the pulse rate slowly after a long latent period.[3] It follows that the first acceleration accompanying work must arise through diminished vagus action.

As to the origin of the nervous influences which act upon the cardiac centers to cause the acceleration during work, several views have been advanced. Hering[4] concluded from his experiments upon the dog that an increased amplitude of respiratory movements gives rise in the lung to impulses which inhibit the vagus center. Examination of the respiratory curves, which accompanied the pulse curves in nearly all my experiments, show that no increase in the amplitude of respiratory movements occurs at the beginning of work; on the contrary, the breathing movements are always diminished at first, and sometimes all but suppressed. Several experiments were made to test the effects upon the pulse rate of such changes in respiratory movements as occur in work. These changes in respiration alone caused only slight effects on the pulse rate, and the usual effects of the work were not in any apparent degree affected, either by voluntary suppression of the breathing or by maintaining it at normal depth and rate during the work. The results of the tests showed plainly that the cause assigned by Hering cannot account for the first acceleration.

Johansson[5] compared the effects of voluntary and reflex movements, and concluded that the impulses causing the change in pulse rate originate in the motor centers of the cerebrum, and that the impulses arising in the muscles

[1] Bowditch and Warren: Loc. cit.
[2] Tigerstedt: Loc. cit., p. 295.
[3] Hunt: Loc. cit., p. 436.
[4] Hering: Loc. cit., p. 491.
[5] Loc. cit., p. 63.

are not important. MacWilliam[1] practically agrees with Johansson. Athanasiu and Carvallo[2] concluded that the impulses coming from the muscles are all important, and that influences from the cerebral centers have no effect on the pulse rate. The latter conclusion is based on experiments made upon paralytics and upon animals poisoned with chloralose,[3] and it seems to me that such experiments cannot be conclusive; for in both cases the cerebral centers are impaired, and would not be expected to discharge motor impulses of normal intensity. Jacob[4] and Egger[5] have shown that sensory stimuli can increase the pulse rate, and Hunt[6] has shown also that impulses from either the brain or a peripheral nerve can cause the acceleration.

The general conclusion to be drawn from all this evidence is that in all probability impulses from both the voluntary brain centers and from the contracting muscles influence the regulating mechanism of the heart and thus inincrease its rate of beat. The latent period of the nerves involved is short enough to make this possible; moreover, the same conclusion is warranted for other reasons.

We know that impulses are discharged from the cortical centers to initiate each voluntary movement,[7] and that impulses arise in the muscles as a result of each contraction.[8] It is also known that such impulses spread to parts of the nervous system entirely outside of their direct paths, and influence other nervous mechanisms, even those which have nothing to do with the work in hand. For example, clenching the hand increases the force of the knee jerk;[9] practice in clenching one hand increases the strength of the other hand.[10] The diffuse spread of impulses which always accompanies vigorous work undoubtedly reaches the cardiac centers and is responsible for the first and most rapid acceleration of the pulse.

The continuation in some cases of an unbroken primary acceleration for two minutes or more (as in the case plotted in Fig. 4) gives ample time for all of the causes of increased heart action to become effective. Some of the influences discussed above as possible causes probably do not aid in the effect at all; reasons will be given for thinking that some of them do not act until later. Some idea of the relative importance of nervous influences in causing the change may be obtained from the fact that in the average pulse rate

[1] Loc. cit., p. 478.
[2] Loc. cit., pp. 554, 567.
[3] Richet: Dictionaire de physiologie. See chloralose.
[4] Loc. cit.
[5] Loc. cit.
[6] Loc. cit., pp. 439 and 446.
[7] Schafer: Text-Book of Physiology, Edinburgh and London, 1900, Vol. II, p. 722.
[8] Sherrington: *Ibid.*, p. 1002.
[9] Lombard: Am. Journ. Psychology, Vol. I, p. 5.
[10] Wissler and Richardson: Psychological Review, 1900, Vol. VII, p. 29.

shown in Fig. 3, fifty-two per cent of the entire rise is accomplished in the first ten seconds and ninety-one per cent in the first thirty seconds. In the heavier work of Table IV, all the way from twenty-two to seventy-five per cent of the rise occurs within ten seconds, and from fifty per cent to one hundred per cent within thirty seconds.

An increase in pulse rate from sixty or seventy up to one hundred or more, which is frequently obtained by tapping a telegraph key as rapidly as possible, seems at first thought scarcely credible as the result of such an insignificant amount of work; and one is likely to conclude that it is not due to the work at all to any large extent, but rather to the psychic conditions brought about by the experiment. In view of the fact that the cause of the change in pulse rate is chiefly or wholly a nervous influence acting on the vagus center, it is entirely correct to speak of it as a psychic influence; but the idea that such a change in pulse rate arises from psychic changes independent of the work can be set aside at once. It was at one time the theory of the writer that the acceleration is due to the condition of nervous tension induced by the effort to work rapidly, and that it can be produced as well by an effort of the will, especially if one imagines the work as being done. It required only a few tests of this matter to prove the fallacy of this view. Seated at the table with the finger on the key, the writer tried again and again, but in vain, to bring about the same acceleration by imagining himself engaged in a desperate trial of speed in tapping against an imaginary opponent, with all the excitement commonly attending an athletic contest. No amount of nervous tension that could be assumed was able to produce one-sixth as much increase in pulse rate as was instantly secured when the finger began to do its work upon the key. The psychic influence, if we choose to call it such, which causes the acceleration, is inseparably associated with muscular work; and the discharge of motor impulses is an essential part of the process causing the increase in pulse rate.

Changes in Pulse Rate from the Completion of the Primary Rise to the End of the Work.

1. *Minor Changes.*—These changes are not seen with any regularity when the pulse is counted in intervals as long as ten seconds. They are seen, however, in many instances, and may be found in nearly all cases by estimating the length of individual cycles. They are not so apparent during the most rapid part of the primary rise, for obvious reasons. As before stated (page 10), the minor changes in pulse rate are usually attributed to respiratory, vasomotor, and psychic changes. Since these influences are present and active during work, as well as when the subject is at rest, it is reasonable to assume that the minor changes during work also result from these causes. No attempt

has been made to study the minor changes in this research, except to recognize their presence and thus avoid confusing them with the effects of work.

2. *The General Course of the Curve of Pulse Rate.*—The main facts on this point, such as the existence of a plateau and a secondary rise, can be readily seen in Tables II, III, and IV. The duration and height of the plateau and the secondary rise, with their relations to the conditions of work, are shown for the bicycle work in Table V. In this group of experiments a plateau seems to be present in every case; the same is true of the lathe work, although in some cases it occurred during the portion omitted from the table. The experiments of Table II are not valid here, for the work was not perfectly uniform in speed and force. It may be observed in Table V that the first five cases of bicycle work gave no secondary rise; the remaining six cases gave a secondary rise continuing to the end of the work. The questions then arise: Would a secondary rise occur in any or all of the first five cases if the work was continued longer; and would the secondary rise in the last six be followed by a plateau on continuing the work for a sufficient time?

TABLE V.

CHANGES IN PULSE RATE DURING BICYCLE WORK, AS RELATED TO THE CONDITIONS OF THE WORK; COMPILED FROM THE SAME RECORDS AS TABLE IV.

Number of Experiment.	Conditions of work.			Effects upon heart rate.					
				Primary rise.		Plateau.		Secondary rise.	
	Revolutions per minute.	Resistance, in Kg.	Work per minute, in Kgm.	Duration. Min. Sec.	Maximum rate per minute.	Duration. Min. Sec.	Average rate per minute.	Duration. Min. Sec.	Maximum rate per minute.
1	30	4.5	71	0:20	80	4:40	78	.....	.....
2	30	11.25	177	0:10	80	4:50	80	.....	.....
3	30	18.	284	0:40	93	4:20	93	.....	.....
4	60	4.5	142	0:20	99	4:40	96	.....	.....
5	60	11.25	354	1:20	115	4:00	111	.....	.....
6	60	18.	568	1:40	137	0:50	137	2:30	147
7	90	4.5	213	1:10	120	4:40	120	1:00	123
8	90	11.25	532	2:00	150	1:20	150	1:20	159
9	90	18.	852	0:50	150	0:30	147	2:30	180
10	60	8.	252	1:20	126	1:00	126	2:20	144
11	60	10.	315	1:10	132	0:50	132	3:00	144

To obtain an answer to the above questions, which were suggested by the results shown in Table V, another series of experiments was made, with the work continued at uniform speed and as nearly as possible under uniform external conditions, for a period varying from half an hour to an hour and a quarter. Of course the work must be moderate to be continued for so long a

time; an amount of work and speed between those of Experiments 5 and 6 was considered the most promising field. The results of this series of experiments are given in Table VI.

TABLE VI.

CHANGES IN PULSE RATE DURING BICYCLE WORK OF LONGER DURATION. ONE SUBJECT.

Number of Experiment.	Conditions of work.			Effects upon heart rate.					
				Primary rise.		Plateau.		Secondary rise.	
	Revolutions per minute.	Resistance in Kg.	Work per minute, in Kgm.	Duration. Min. Sec.	Maximum rate per minute.	Duration. Min. Sec.	Maximum rate per minute.	Duration. Min. Sec.	Maximum rate per minute.
12	60	12.5	375	1:00	114	5:00	114	25.00	142
13	60	12.5	375	1:20	114	15:00	111	20:00	126
14	60	12.5	375	1:40	114	10:00	117	40:00	138
15	60	10.	300	1:40	108	4:00	108	55:00	123
16	45	10.	225	1:00	93	30:00	93	40:00	98
17	45	6.6	150	0:40	96	60:00	97	.....	.....

The above results indicate that we are likely to have a secondary rise following the plateau when the work is prolonged, even when it is very light; but No. 17 suggests that there may be no secondary rise if the work is made light enough. As a test of the same point the writer worked a key continuously for forty-six minutes at the rate of four per second against a resistance of 1 kg. In this case also no secondary rise occurred, although the work was severe enough to cause intense local fatigue.

There is no indication in any of these cases of the occurrence of a second plateau following a secondary rise; in fact, the rise appears to increase rather than decrease as the work continues. The only exception to this rule in all the experiments made by the writer is in case of No. 9 of Table IV, where the pulse rate reached the unusual height of 180, and continued at this rate for nearly two minutes. It is possible that in this instance the heart reached its maximum rate, although Kolb[1] and Mendelsohn[2] claim that it may exceed 200 in trained men.

Grünbaum and Amson[3] conclude from the results of nineteen experiments that the pulse rate tends to rise continuously as long as the work lasts. The occurrence of a plateau having a duration of at least thirty seconds in every one of the twenty-eight cases given here indicates that this statement should

[1] Loc. cit., p. 114.
[2] Loc. cit.
[3] Loc.cit., p. 551.

be modified; the performance of work continuously for an hour with no permanent increase in pulse rate after the first forty seconds shows that the rule does not apply under all conditions. My experiments, like theirs, have been made upon a small number of subjects, and individual differences may color the results; but as far as my experiments go, they show that on beginning muscular work there is always a rapid primary rise of pulse rate which is followed by a plateau of varying length containing minor changes; and that under certain conditions, of which rapidity of movement is probably most important, the plateau is followed by a slower secondary rise, which continues to the end of the work.

3. *Causes Operating to Produce the Plateau and the Secondary Rise.*—The cessation of the primary rise and the occurrence of an approximately uniform pulse rate during work indicates that the forces determining the rate of the heart have reached an adjustment, in which the causes producing the rise must be considered as continuing. This, it seems to me, is the only way to explain the occurrence of the plateau, which is a constant characteristic of the pulse rate in all uniform light work and in most cases of heavier work.

The occurrence of a secondary rise, separated from the primary rise by a plateau of such length as to render its presence unmistakable, is a phenomenon not recognized by previous writers. Such a rise distinctly indicates the presence of a cause of acceleration not operating before. It is not to be attributed to increased intensity of nervous discharge necessitated by increasing fatigue, for in light work pushed to extreme fatigue no secondary rise occurs. The secondary rise seems to be associated with rather rapid work of large muscle groups, which suggests the agency of the group of causes connected with muscular metabolism. Athanasiu and Carvallo[1] favor this cause, especially in prolonged work, and state as evidence that the return to the normal rate on stopping is hastened by respiring oxygen and retarded by suppressing the breathing. The gradual character of the rise corresponds with the effect which Johansson[2] attributes to waste products.

In the experiments of Table VI the temperature of the body was tested every five minutes by means of a clinical thermometer placed under the subject's tongue. The results are consistent in all of the cases, the manner of the change being similar in each case to that shown in Fig. 5,which was plotted from the results of Experiment 15. It seems clear that the secondary rise is not to be accounted for by the direct effect of the change in temperature and that alone, for the pulse rate, as may be seen in the figure, remains constant for a part of the time during which the temperature is rising, and continues to rise after the temperature has reached its maximum and has begun to fall.

[1] Loc. cit., p. 361.

[2] Loc. cit., p. 61.

A considerable increase in the amplitude of the respiratory movements occurs in all heavy work, but not in the earlier stages. It is not possible, however, to observe any marked change in this respect at the time the secondary rise begins, and therefore there is not sufficient ground for assuming any

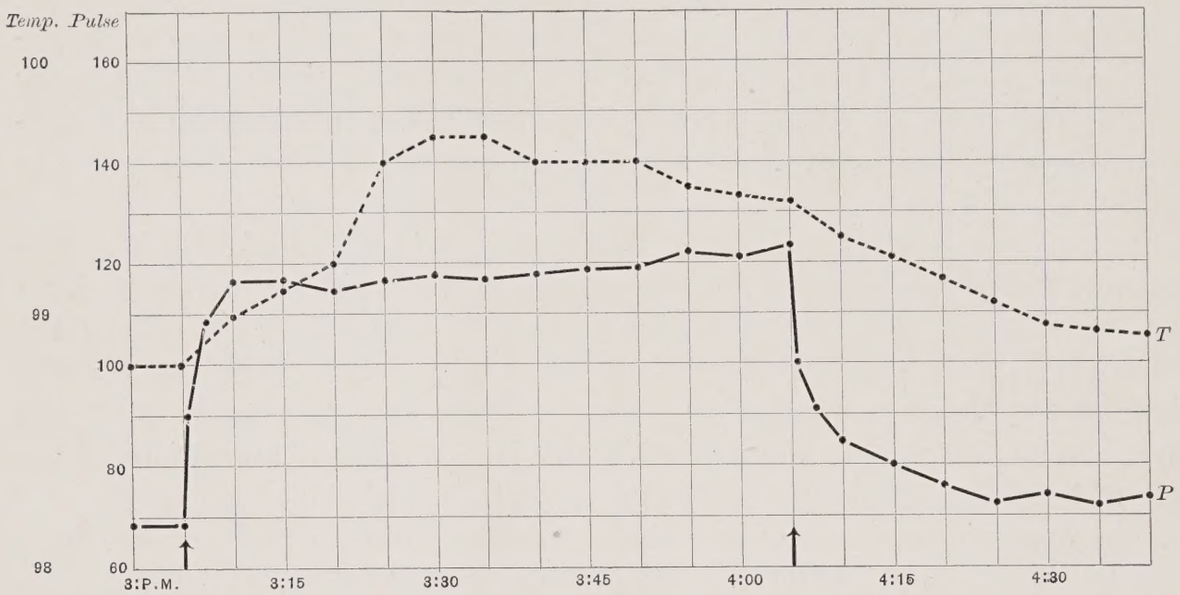

FIG. 5. Changes in pulse rate and temperature of the body during a bicycle ride of one hour and during rest for the half-hour following. The solid line (P) indicates the pulse rate and the broken line (T) the temperature. Arrows indicate the beginning and end of the work.

relation of these two effects of the work, such as to make one the cause of the other.

To summarize, we may say that the secondary rise is probably caused by some influence not acting in earlier stages, with indications in favor of the agency of waste products of muscular action and indirect effects of increased temperature of the body.

THE CHANGE IN PULSE RATE WHEN WORK CEASES.

Upon the cessation of work the pulse rate falls in a manner precisely similar to its primary rise; very rapid at first, gradually diminishing in rapidity as it continues, and finally returning to the normal rate. A glance at any of the plotted curves shows this fact plainly. In the lightest work, where no secondary rise occurs, there is no secondary fall—the curve falling quickly to the level it followed before the work. (See Fig. 3.) When the work is such as to give a secondary rise, there is also a secondary fall, as shown in Figs. 4 and 5. The two stages of fall, like the two stages of rise during work, are frequently separated by a plateau. The changes in pulse rate during the period of recovery after work have been studied extensively, especially by

Staehelin;[1] therefore it has not seemed worth while in this research to continue the records in all cases through this period, which may occupy an hour or more. Staehelin's records include only thirty seconds out of each consecutive five minutes, and consequently they do not show the changes as fully as mine; yet the two stages of fall with the intervening plateau can be seen in many of his tables, although he does not call attention to them.

The primary fall of pulse rate following the cessation of heavy work is not usually so rapid nor so extensive as the corresponding rise. In general, the heavier and more rapid the work, the higher does the plateau separating the two periods of fall stand above the normal rate.

The great rapidity with which the pulse rate changes at the beginning and at the end of work emphasizes the importance of studying the effect of work while it is going on. A count of the pulse or a graphic record taken after the work has ceased can give no information whatever of the character of the changes in heart action during the work; its evidence as to the amount of acceleration that actually occurred as a result of the work is always unreliable, and when the length of the delay is not known it is absolutely worthless. The following table of pulse rates, recorded of different men during work of different kinds, will illustrate.

Kind of work.	Max. rate during work.	1st. 10 sec. after work.	2nd. 10 sec. after work.	30 sec. count after five seconds delay.
Light.....	102	69	62	62
Moderate	150	138	123	120
Heavy.....	180	174	162	164

The results in the second column, the best possible by the old methods, are from three and one-third per cent to thirty-two per cent below the actual maximal, as given in the first column; the figures in the other two columns, those obtained by most observers, are from ten per cent to thirty-nine per cent less than the correct results. This deficiency in former methods of determining the pulse rate resulting from work will go far in explaining the low estimates given by text-books, and will also account for the failure to observe the rapid pulse that may result from light rapid work.

Conditions Determining the Rapidity of the Pulse During Work.

1. *The Quantity of External Work.*—It has been commonly assumed by writers on this subject that the rapidity of the pulse resulting from work is determined chiefly by the quantity of work, as registered by the machine upon which the work is done. My results substantiate this theory only to a very limited extent. Arranging in a continuously increasing series the

[1] Loc. cit., Bd. LIX, p. 118–139.

amounts of work done in fifteen experiments on the bicycle, and placing below each amount of work the maximal pulse rate resulting from it, we have as follows:

Work	71	142	150	177	213	225	252	284	300	315	354	375	532	568	852
Pulse	82	102	97	84	123	98	144	97	123	144	115	142	159	147	180

It is possible to observe here a tendency for the pulse rate to increase as the work increases; but if any such relation exists as is usually assumed, each increase in work should be accompanied by an increase in pulse rate. We find, on the contrary, that the expected increase in pulse rate accompanies the increase in work in only eight instances out of fourteen, and that in one instance (142–284), doubling the work results in an actual decrease in pulse rate (102–97), while several other exceptions are almost as striking. The indication is plain that the rapidity of the pulse in these cases is not determined to any large extent by the quantity of work done.

Christ, Staehelin, and Grünbaum and Amson all arrange their results in a form similar to the above, and all show an apparently close relation of work and pulse rate; the latter writers show a continuous increase in pulse rate to correspond with the increasing work. This is easily explained by the fact that in their experiments the increase of work involved simply an increase in one factor without changing others; in no case was an increase of one of the three factors—speed, resistance, and duration—accompanied by a decrease in another. This means that no test of the separate influence of these three factors was involved. A comparison of my results in similar instances shows the same thing; increased resistance with constant speed always gives a higher pulse rate. Such comparisons are not sufficient to prove a relation of work and pulse rate, for they leave out of account the only conditions which could be expected to give a different result.

It is evident in the first place that if any relation exists between pulse rate and quantity of work, it must be a relation of pulse rate to the work actually done by the contracting muscles, rather than to the external work accomplished; and one reason why the pulse rate fails to correspond with the quantity of external work is because the external work is such an imperfect measure of the work performed by the muscles in accomplishing it. It is a familiar fact that for any muscle group there is a certain range of resistances and speeds within which it works without other muscles being called into action; but as soon as either speed or resistance exceeds the limit, additional muscles are contracted, and this may become so extensive as to include practically all the voluntary muscles. Now, the work of these extra muscles must influence the heart as well as that of the muscles acting directly upon the machine in use; it follows that a change in the quantity of external work may or may not require a proportionate change in the work of the muscles, and that the accomplishment of a given quantity of external work may require

widely different amounts of work by the muscles, depending upon the speeds and resistances employed. We are compelled to conclude that speed and resistance are factors requiring separate consideration.

2. *Speed and Resistance.*—In order to study the relative importance of these two factors it is necessary to make quantitative comparisons; Table VII has been arranged to show more clearly the relations existing among the first nine experiments upon the bicycle.

TABLE VII.

RELATIVE IMPORTANCE OF SPEED AND RESISTANCE IN DETERMINING THE RAPIDITY OF THE PULSE DURING WORK. THE RATES GIVEN ARE MAXIMAL FOR EACH CASE.

Resistance.			Speed.		Work.	Pulse rate.	
Cases compared.	Increased from.	Constant.	Increased from.	Constant.	Increased from.	Increased	
						From.	Per cent.
1 and 2	4.5 to 11.25			30	71 to 177	82 to 84	2.2
1 " 4		4.5	30 to 60		71 " 142	82 " 102	24
1 " 3	4.5 " 18			30	71 " 284	82 " 97	18
1 " 7		4.5	30 " 90		71 " 213	82 " 123	49
4 " 5	4.5 " 11.25			60	142 " 354	102 " 115	12
2 " 5		11.25	30 " 60		177 " 354	84 " 115	37
4 " 6	4.5 " 18			60	142 " 568	102 " 147	44
2 " 8		11.25	30 " 90		177 " 532	84 " 159	89
7 " 8	4.5 " 11.25			90	213 " 532	123 " 158	29
3 " 6		18	30 " 60		284 " 568	97 " 147	51
7 " 9	4.5 " 18			90	213 " 852	123 " 180	46
3 " 9		18	30 " 90		284 " 852	97 " 180	85

The resistance of 4.5 in Case 1 was increased 2.5 and four times to give the higher resistances used in this series, and the speed of thirty revolutions per minute was increased two and three fold to give the higher speeds; it follows that the increase in quantity of work due to changes in resistance is twenty-five and thirty-three and one-third per cent more than the corresponding increase in quantity of work due to changes in speed. In spite of this marked advantage in favor of the resistance, the changes in speed have much the greater effect on the pulse rate. By reference to other experiments recorded in the preceding tables, other comparisons could be made similar to those shown in Table VII, with the same conclusion in every instance. If we compare any two cases of work by the same subject in which the quantity of work is nearly the same, the one in which the speed is greater invariably has the higher pulse rate. An interesting instance of this kind may be seen in Cases 5 and 7 of Table III. In these two experiments the quantity of external work was the same, No. 5 having double the resistance and half the speed of No. 7.

To test the same point with lighter work, four experiments were made which are reported in Table VIII. The lever of a telegraph key was depressed through a space of 1 mm., first against a resistance of forty grams with a speed of five per second, and then, at the same sitting, but after a rest, against a resistance of 1.6 kg. with a speed of one movement per second. The total external work in the latter case was eight times as great as in the former, and the extra work done by the muscles was also much in excess in the same case; the light work at five per second requiring practically no work beyond that done by the muscles in moving the finger, while the greater resistance required a movement of the whole arm. Yet, in spite of such advantage, the lighter and more rapid work caused double the acceleration of the pulse.

TABLE VIII.

CHANGES IN PULSE RATE DUE TO LIGHT WORK, ILLUSTRATING THE RELATIVE IMPORTANCE OF SPEED AND RESISTANCE IN THE ACCELERATION OF THE PULSE.

Subject.	Resting before work.	Working 40 g. 5 times per second.	Resting before work.	Working 1.6 kg. once per second.
W. P. B.	75.1	83.3	74	79.3
C. L. B.	80	84.6	83.3	87.4
B. D. N.	65.2	75.8	69.4	73.1
F. W. S.	82.2	96.2	84	90.1
Average rate	75.6	84.9	77.7	82.5
Average acceleration		9.3		4.8

The results given in Table II show a maximal pulse rate whose average is ninety-three. This rate is produced by movements of great rapidity, requiring an expenditure of external work not exceeding 0.025 kgm. per minute. If we look at Tables V and VI we find that to produce a rate of ninety-three by means of the heavier and slower bicycle work requires a performance of between 200 and 300 kgm.—from 8,000 to 12,000 times the amount of external work required when the movements are more rapid. On the assumption that the quantity of external work is what determines the pulse rate, this is not easy to explain.

The number of my experiments bearing upon this point is not great, and the number of subjects still smaller; but as far as they go they indicate unanimously and decidedly that speed has far greater influence upon pulse rate than resistance; in the absence of any opposing evidence the indication is believed to be correct. In addition to the experimental evidence, the following reasons are given in support of this view:

a.—Muscles work more economically with high than with low resistances. It was shown by Haidenhain[1] that for each muscle there is a certain resistance against which it works most economically; that is, when it has the resistance

[1] See Burdon-Sanderson: Schäfer's Physiology, Vol. II, p. 397.

best suited to its strength it will do a given amount of work with less katabolism, and less energy will be lost in the form of heat, than with any other resistance. This most favorable resistance is about half of the amount the muscle can lift. The highest resistance employed in these experiments is less than one-fourth of the amount the muscles can overcome, and this is as heavy work as has been used in most experiments made on this subject. It follows that such work has been done more and more economically as the resistance has been increased. The activity involved in developing energy that is afterwards wasted must influence the heart as well as when it is employed for the purpose in view; the slower and more economical work will for this reason have proportionately less effect on the pulse rate.

b.—The more rapid the movements, the more extra work is required to move parts of the body. Every bodily movement involves considerable expenditure of energy in overcoming the weight and inertia of the part moved. Extra work of this kind is especially important in such movements as running, rapid walking, or working a treadle, where the limb must be brought back to the starting-point with great swiftness after each movement. It is not only necessary in the most rapid movements to move the limb, but it is moved so swiftly that force is required to stop it at the end of its course. Work wasted in this way must aid in quickening the pulse, and the waste increases in direct proportion to the speed of movement.

c.—A diffuse spread of nervous impulses accompanies movements of great rapidity, causing the contraction of muscles that are not useful. This must aid in cardiac acceleration, both because of the scattering of impulses, which may act upon the cardiac centers, and because of the number of muscles brought into action.

d.—A rapid shower of light impulses will excite a reflex when a slower succession of impulses will fail. In the same way a more rapid shower of impulses may be a more effective irritant of the cardiac centers than a slower succession of impulses, even when the latter are of greater intensity.

The Relative Duration of Systole and Diastole, as Influenced by Muscular Work.

It has been shown by Edgren[1] and by Hürthle[2] that any heart cycle, considered as extending from one primary upstroke of the pulse curve to the next, is divided by its dicrotic notch approximately into its systolic and diastolic portions. While making the experiments recorded in Table I the writer noticed that the dicrotic notch is fully as sharply defined in the curves as the primary wave itself; the possibility of studying the effect of work upon the

[1] Loc. cit., p. 145.

[2] Arch. f. d. ges. Physiol., Bd. XLIX, p. 66.

two parts of the cycle was at once suggested. By reference to the curves used in compiling Table I it was found that with light work the acceleration of the pulse is due almost exclusively to a shortening of the diastole. The results given in Table IX, which were taken from the records of eight different subjects, illustrate this point. The figures were obtained by averaging the duration of systole and diastole for 6–12 consecutive cycles in the resting period and again in the working period. The change in diastole sometimes exceeds fifty per cent; the change in systole did not exceed ten per cent in any of these cases.

TABLE IX.

CHANGES IN THE DURATION OF SYSTOLE AND DIASTOLE ACCOMPANYING LIGHT WORK. THE FIGURES GIVEN ARE HUNDREDTHS OF A SECOND.

Subject.	Resting.		Working.		Decrease.	
	Systole.	Diastole.	Systole.	Diastole.	Systole.	Diastole.
O. P. C. .	27.	66.5	26.2	51.7	0.8	14.8
A. A. B. .	29.5	85.	28.	66.	1.5	19.
R. C. R. .	29.	66.2	26.2	48.6	2.8	18.6
E. A. B. .	24.	51.	24.	40.	0.0	11.
J. D. M. .	28.	78.	26.	38.	2.0	40.
C. J. L. ..	26.8	69.	28.	50.4	1.2(inc.)	18.6
W. P. B.	26.	48.6	26.	38.2	0.0	10.4
B. D. N. .	30.5	72.2	30.	40.	0.5	32.2

As the records afterwards used in compiling Tables II and VI could not be utilized for this purpose, being taken on slow drums and timed in seconds, a plan was devised for recording brief pulse curves on a fast drum along with a fork at any desired time during the progress of an experiment, without breaking the continuity of the longer and slower record. A second T-tube was inserted in the course of the rubber tube connecting the two tambours, and a branch tube was carried to a second recording tambour, which writes on a second drum along with the fork. The carotid pulse was found to have ample force for writing the two curves at once. By keeping the second drum moving at suitable speed during an experiment, a short record giving an opportunity for studying the changes in systole and diastole may be taken at any time by starting the fork and bringing the writing points of fork and second recording tambour against the second drum. A simple device making a metallic contact at the instant the writing points touch the paper causes an electric signal to mark on the first record the exact time during which the second record is being taken. Two corresponding records taken at once on the two drums are shown in Fig. 6; Fig. 7 gives other examples of curves recorded on the second drum.

The tambours were given a series of tests to make sure that the tendency of their membranes and levers for periodic vibration would not prevent their

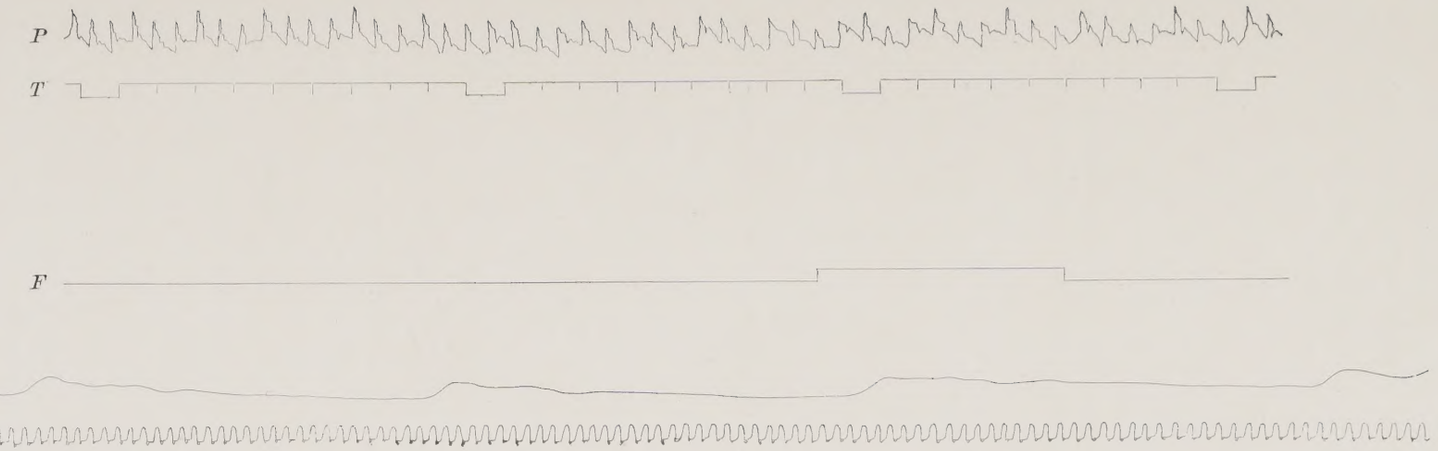

FIG. 6. Records showing the manner of indicating the time relations of two pulse curves taken at once. *A*, record on slow drum; *B*, record on rapid drum; *P*, pulse curve; *T*, time in seconds; *F*, record indicating the time during which the second record is being taken; *p*, portion of pulse curve on second drum, showing its third, fourth, and fifth pulse waves; *t*, time in fiftieths of a second.

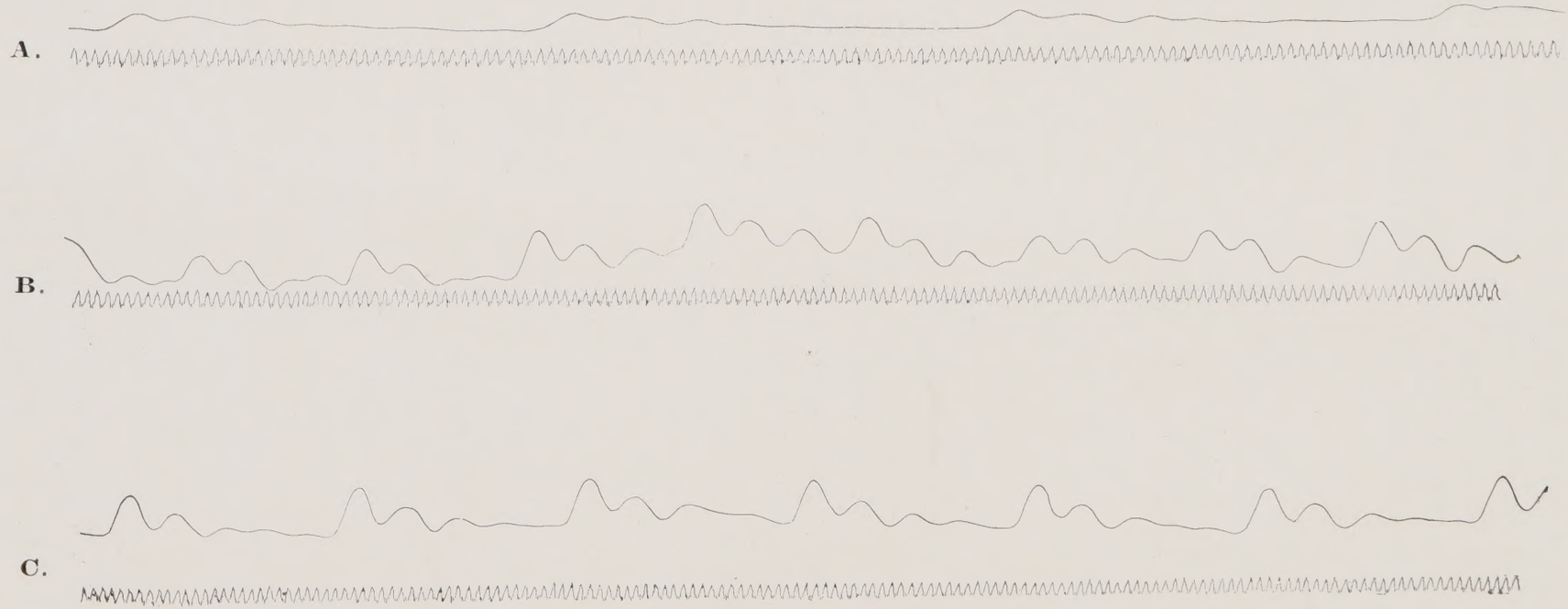

FIG. 7. Pulse curves recorded on fast drum along with fork vibrating fifty times per second, at intervals during the progress of Experiment 9 of Table IV. *A*, before work; *B*, during the heavy work; *C*, shortly after work ceased.

recording the pulse waves in correct time. The natural vibration period of the tambours was found to be very short—between 0.03 and 0.04 seconds—and their amplitude so small that no indication of any interference with the much greater pulse waves could be detected. Moreover, pulse waves varying in length from 0.08 to 0.45 seconds were recorded readily, so that there seems to be no occasion to discredit the apparatus.

TABLE X.

CHANGES IN DURATION OF SYSTOLE AND DIASTOLE, EXPRESSED IN HUNDREDTHS OF A SECOND. SHOWING THE EFFECT OF VIGOROUS WORK ON A BICYCLE. TWO SUBJECTS.

Number of experiment.	Before work began.		Soon after beginning work.		Near time of maximal pulse rate.		Soon after work ceased.		Several minutes later.	
	S.	D.	S.	D.	S.	D.	S.	D.	S.	D.
1	25.2	55.4	26.5	33.2	26.4	36.0	24.4	49.4	24.6	53.3
2	26.0	64.7	28.0	34.0	25.2	31.0	25.0	32.0	26.0	56.5
3	25.0	58.7	24.8	26.0	20.4	20.9	19.0	22.5	22.0	43.0
4	24.8	47.2	25.4	28.4	22.0	20.0	22.4	30.0	23.8	38.4
5	26.8	64.0	26.0	34.0	22.0	28.0	22.0	40.0	25.0	63.0
6	27.0	66.0	28.0	42.0	20.0	25.0	20.5	33.0	25.0	62.0
7	25.5	69.5	27.5	40.5	21.0	28.0	22.0	42.0	25.0	57.0

Table X gives results obtained in the manner just described during the progress of several experiments upon the bicycle. Here the greatest change in systole is nearly twenty-five per cent, and the greatest change in diastole sixty-

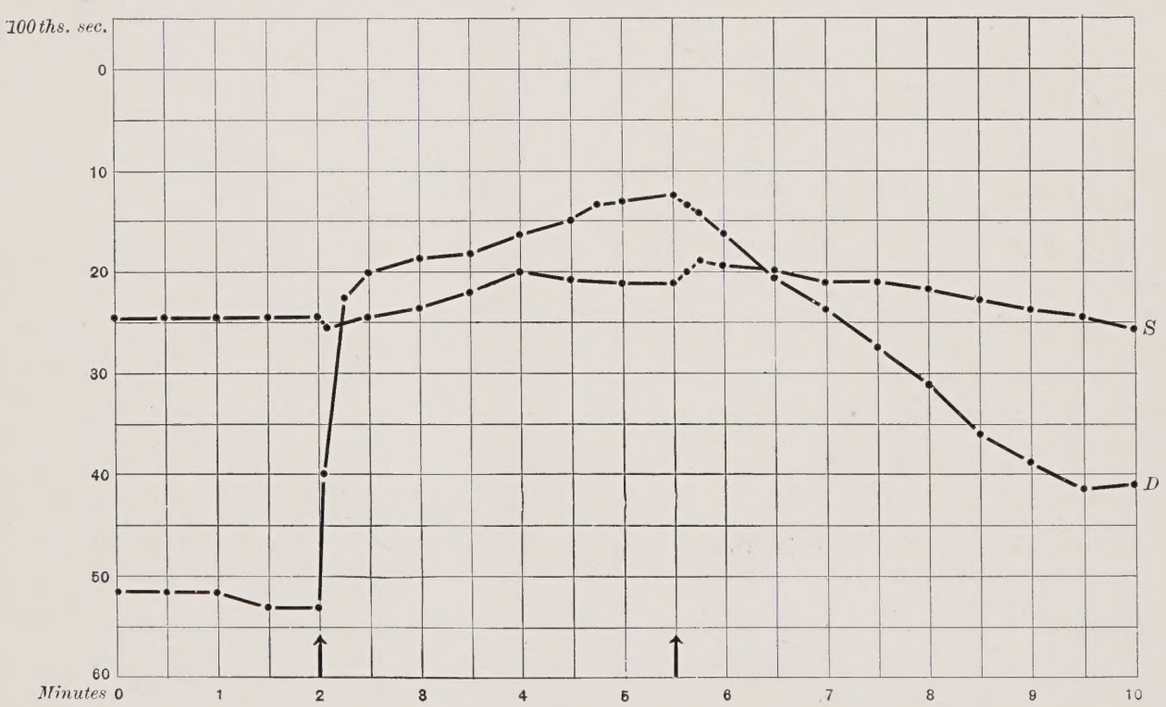

FIG. 8. Changes in duration of systole and diastole due to heavy and rapid work upon a bicycle. *S*, curve of systole; *D*, curve of diastole. Arrows indicate the time of the beginning and cessation of work.

six per cent. In the curves of Fig. 7, which were taken during an experiment involving more violent work than any in this table, the systole shows a change of nearly thirty per cent and the diastole about eighty per cent. The changes in duration of systole and diastole found in this experiment are plotted in the curves of Fig. 8. This figure shows a shortening of diastole until it is less

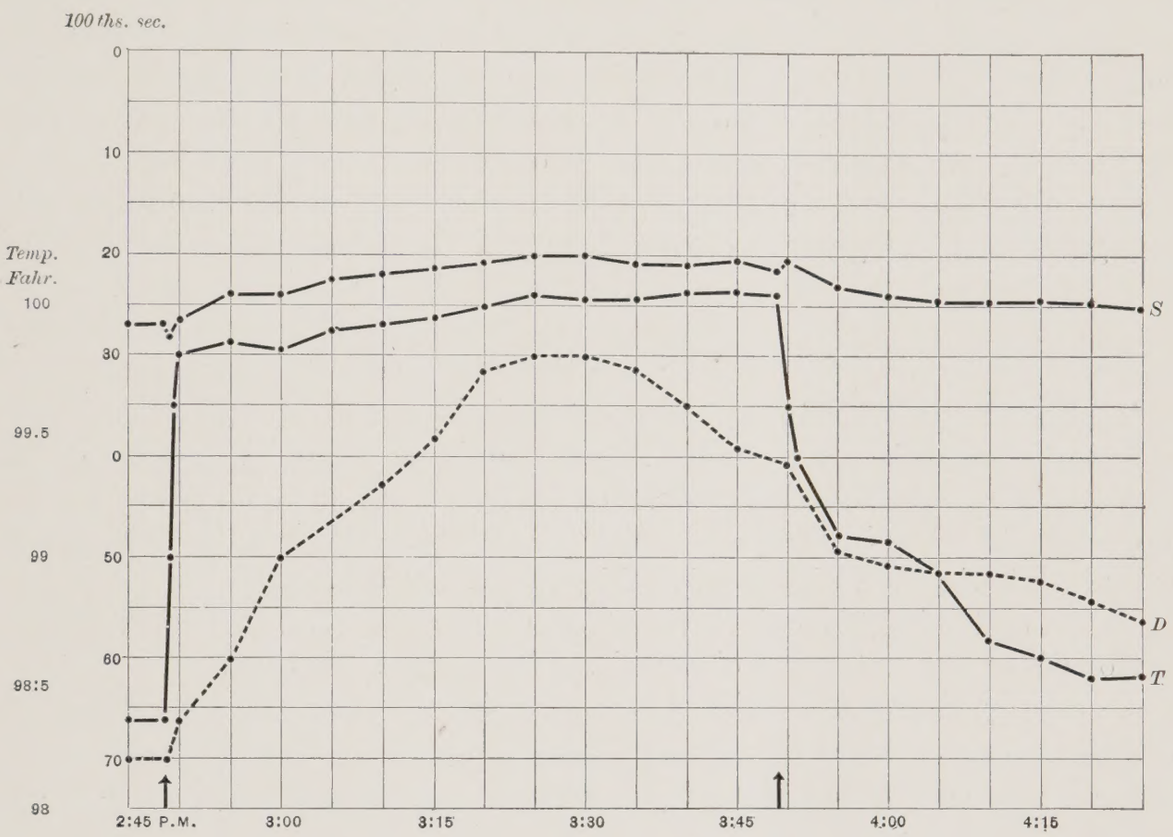

FIG. 9. Changes in duration of systole and diastole due to moderate bicycle work of fifty-two minutes' duration. *S*, curve of systole; *D*, curve of diastole. Arrows indicate time of beginning and cessation of work. *T*, curve of temperature of the body.

in duration than the corresponding systole—a condition also present in No. 4 of Table X, and in all cases in which the pulse rate exceeded 135 per minute. Zuntz and Schumburg[1] have observed this fact in curves recorded immediately after heavy marching.

One of the most striking points to be observed in Table X is that immediately after the beginning and end of the work, when the diastole is changing most rapidly, the systole changes in the opposite direction. There are a few exceptions to this rule in the table, but an examination of the records shows that they probably occur because the record was not taken quickly enough after the beginning and end of the work. After this short period of reverse change, the systole shortens during work and lengthens after work

[1] Loc. cit.

ceases, but much more slowly and gradually than the diastole. The manner of these changes is well illustrated by the curves of Fig. 9, which were plotted from fork records taken during the progress of No. 14 of Table VI.

It seems to have been tacitly assumed by those who studied the time relations of systole and diastole in former years that a certain pulse rate always involves a definite relation of the lengths of these two parts of the heart cycle, no matter what cause was acting to produce the pulse rate under consideration. Chapman went so far as to draw up a table giving the exact duration of systole for all pulse rates from 45 to 200. His results, up to a rate of 130, were based upon graphic records taken from cases in which the higher pulse rates resulted from fever, muscular work, Turkish baths, and unknown causes; the figures for still higher rates were computed from these, on the assumption that the changes would continue in the same ratio. The results obtained by Zuntz and Schumburg and by the writer for pulse rates above 130 fail to agree with the predictions of this table; and there are indications that changes in systole and diastole are to a certain extent independent of each other, their relations being different when the acceleration results from different causes. Chapman's results also indicate this, for his figures for duration of systole are proportionately less in every case where the acceleration resulted from fever or Turkish baths than when produced by muscular work.

As it is intended to continue the study of this point further, no other discussion of the results thus far obtained will be made at this time.

In closing, the writer wishes to acknowledge the invaluable assistance of Professor W. P. Lombard, without whose kindly and able suggestions the piece of research here described could not have been successfully carried on.

Summary of Results.

1. Muscular work is accompanied by a marked acceleration of the pulse, which begins with the next heart cycle after the work begins, and in typical cases shows three well-marked stages: a primary rise, a plateau, and a secondary rise. Similar stages of decrease in rate occur after the work stops.

2. The primary rise is exceedingly rapid, sometimes amounting in the first ten seconds to thirty per cent of the preceding rate; it is most rapid at the start, and gradually diminishes until the plateau is reached.

3. The plateau, which contains small changes of short duration, often continues in cases of light work for an hour or more, and may continue as long as the work lasts.

4. When the work is at all vigorous, the plateau, which in such cases may be brief, is followed by a secondary rise, which is more gradual than the primary rise, and which continues to the end of the work.

5. During the first few seconds of heavy work, and for the entire period of the lightest work, the acceleration is due almost exclusively to a shortening

of diastole; the systole is also shortened considerably in heavy work, after the first few seconds.

6. When the pulse rate accompanying work reaches 135 per minute, the diastole is usually as short as the systole; for higher rates the diastole is the shorter.

7. The rapidity of the pulse during work depends not only upon the amount of work done, but much more upon the manner in which it is done. Speed and resistance are factors requiring separate consideration, and of the two speed has much the greater influence.

8. Graphic records of the pulse can be readily taken during the progress of vigorous muscular work.

Conclusions.

1. The latent period of the human heart, when influenced by muscular work, is in the vicinity of one heart cycle.

2. The first and most rapid increase in pulse rate accompanying work is due to a diminution of the restraining influence of the inhibitory center, caused by nervous impulses arising in the motor centers of the cerebral cortex, or in the nerve endings in the muscles, or in both.

3. Later continuation of the change is probably due in part to nervous impulses stimulating the accelerator center, and to heat and waste products developed in the heart; still later, in heavy work, heat and products of muscular metabolism may aid in further increase.

4. The plateau must result from a continuation of the causes producing the primary rise; the secondary rise, from causes not acting before.

5. The changes in pulse rate during work and at its end are so sudden and so rapid that the only reliable information concerning them must be acquired while the work is in progress; for this purpose a continuous graphic record is far superior to any other method that has been employed.